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Atmosphere–vegetation–soil interactions in a climate change context; impact of changing conditions on engineered transport infrastructure slopes in Europe

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Abstract: In assessing the impact of climate change on infrastructure, it is essential to consider the interactions between the atmosphere, vegetation and the near-surface soil. This paper presents an overview of these processes, focusing on recent advances from the literature and those made by members of COST Action TU1202 – Impacts of climate change on engineered slopes for infrastructure. Climate- and vegetation-driven processes (suction generation, erosion, desiccation cracking, freeze–thaw effects) are expected to change in incidence and severity, which will affect the stability of new and existing infrastructure slopes. This paper identifies the climate- and vegetation-driven processes that are of greatest concern, the suite of known unknowns that require further research, and lists key aspect that should be considered for the design of engineered transport infrastructure slopes in the context of climate change.

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Reliable performance of engineered transport infrastructure slopes (embankments and cuttings) is a critical component of the stability of any transportation network. The complex patterns and interactions driven by atmosphere–vegetation–soil interactions play an important role in the stability of these slopes (Fig. 1). It is important to understand the transient processes in these engineered soils, particularly when it is clear that, as a consequence of climate change, simple extrapolations from past observations are no longer valid for determination of future performance (e.g. Dijkstra & Dixon 2010; Glendinning *et al.* 2015).

COST Action TU1202 is a coalition of researchers that addresses the challenges of engineered slope infrastructure resilience in a context of climate change in Europe. Working Group 3 (Climate–vegetation–soil interactions) from this Action focuses on the understanding of long-term climate impacts on slope stability, by developing an interdisciplinary approach from a geotechnical engineering–engineering geology–hydrogeology–hydrology perspective.

Complexities are already significant in terms of atmosphere–soil interactions, and vegetation effects create a further dimension. In this complex hierarchy of processes, both positive and negative feedbacks interact to drive a system in which stabilizing and destabilizing components compete for dominance.

This paper aims to draw together an overview of the outcomes of the COST Action TU1202 workshops and discussion fora, and reflects on recent advances and a range of facets of atmosphere–vegetation–soil interactions. The quantitative analysis of vegetation, soil and atmosphere systems constitutes a major challenge to scientific disciplines and policymakers, especially when climate change results in a non-steady-state environmental context in which these processes operate.

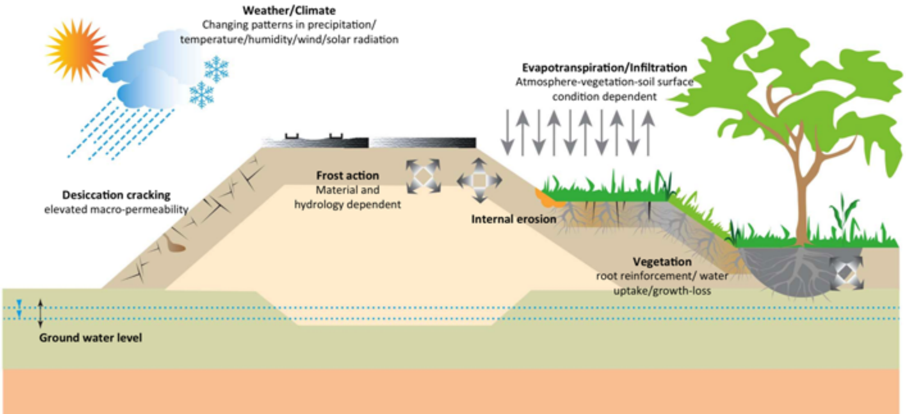

Fig. 1. Schematic view of the soil–vegetation–atmosphere interactions (modified from Vardon 2015).

First, the paper discusses climate change briefly, as it applies to the European context, and then the following are discussed: (1) climate-driven processes that are of greatest concern, including comments on the suite of known unknowns that require further research; (2) key aspects that need to be considered for design, operation and maintenance of engineered transport infrastructure slopes.

It is impossible to address all relevant processes and phenomena in one paper and the current selection reflects the key topics discussed during the COST action workshops. Further elaborations on modelling implications, the role of instrumentation and issues of risk management are discussed in accompanying papers that are part of this special set (Elia *et al.* 2017; Smethurst *et al.* 2017; Gavin *et al.* in review).

Climate change context

Climate change is now known to occur, but determining the potential impact on engineered transport infrastructure slopes is still difficult (e.g. Dijkstra & Dixon 2010; Glendinning *et al.* 2015).

Key headline climate change messages include the following (IPCC 2014).

- Recent climate changes have had widespread impacts on human and natural systems.
- Warming of the climate system is unequivocal, and since the 1950s many of the observed changes are unprecedented over decades to millennia.
- In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate.
- Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heatwaves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions.
- Climate change will amplify existing risks and create new risks for natural and human systems.

In the future the European environment will have to face climate change impacts that are expected to be even stronger and more numerous than in the past (EEA 2015*a*). The projected rise in global average temperatures over the 21st century is 0.3–1.7°C for the lowest emission scenario, and 2.6–4.8°C for the highest emission scenario (IPCC 2013, 2014). Annual average land temperatures over Europe are projected to increase more than the global average temperature. The largest temperature increases are projected over eastern and northern Europe in winter, and over southern Europe in summer (Fig. 2). Annual precipitation is generally projected to increase in northern Europe and to decrease in southern Europe (Fig. 3), thereby enhancing the differences between currently wetter regions and currently drier regions. The intensity and frequency of extreme weather events is also projected to increase in many

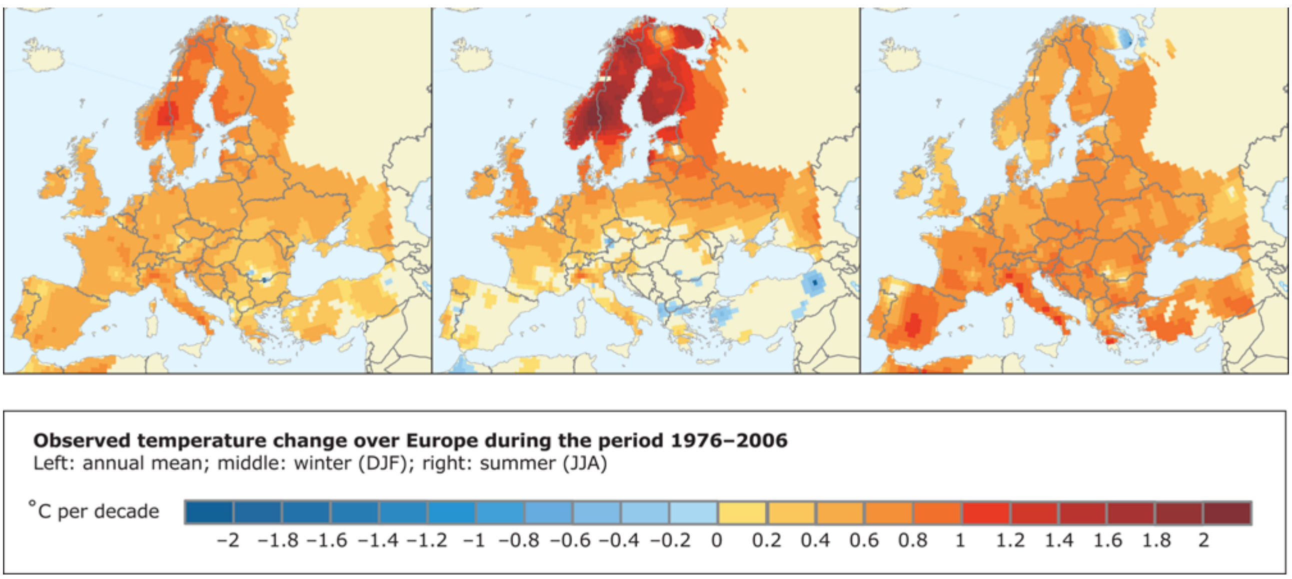

Fig. 2. Observed temperature change (1976–2006) (from EEA 2009).

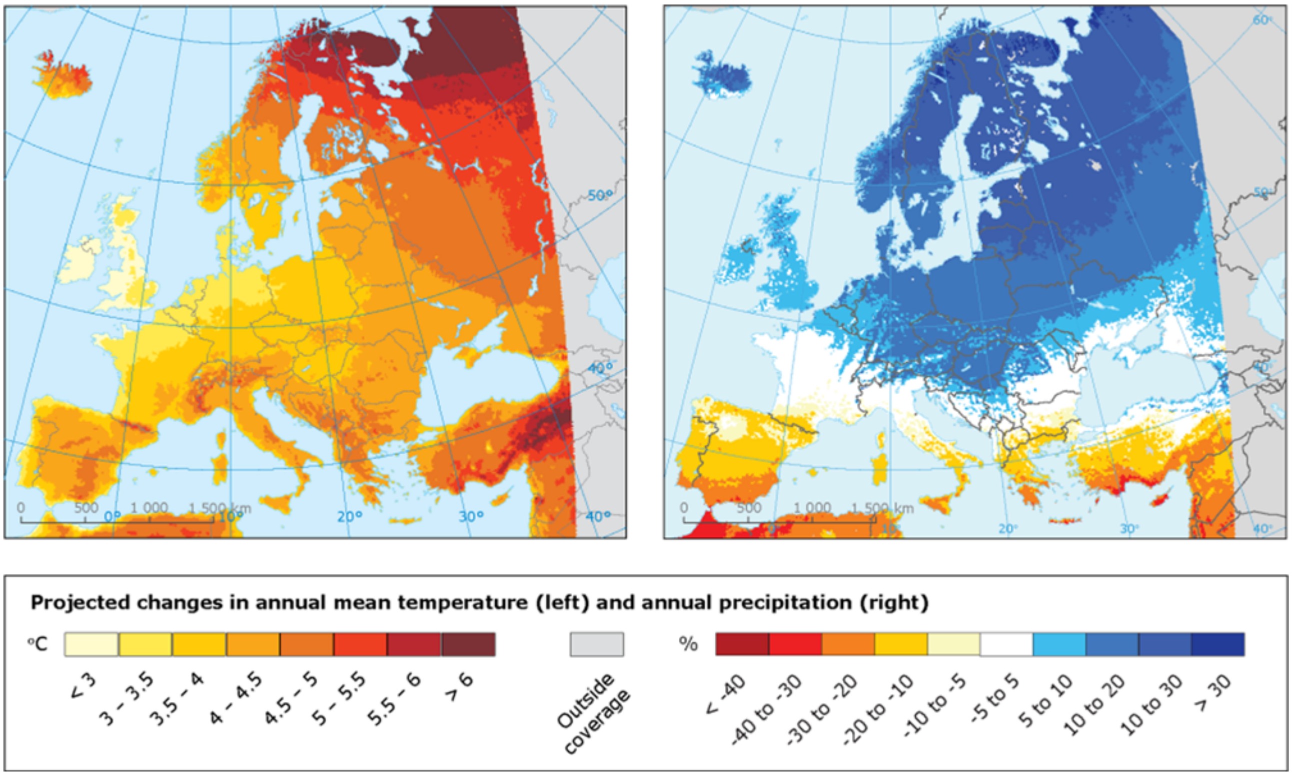

Fig. 3. Projected temperature and precipitation changes for the period 2071–2100 compared with 1971–2000 based on an ensemble of regional climate model simulations provided by the EURO-CORDEX initiative (from EEA 2015*b*).

regions, and sea-level rise is projected to accelerate significantly (EEA 2012). Underlying the global trends are important regional variations and the effect on the resilience of transport infrastructure slopes has to be considered at the regional scale.

In Europe, there have been increases in the frequency and/or intensity of heavy precipitation with some seasonal and regional variations. The temperature of land area over the period 2002–2011 has been 1.3°C above the pre-industrial level on average, meaning that the increase in Europe has been faster than the global average (EEA 2015*a*).

National climate projections can be very informative for modelling the climate change effect on the local scale; for example, UKCIP (Jenkins *et al.* 2008) and KNMI scenarios (Van den Hurk *et al.* 2006). The impact of climate factors differs greatly between geographical locations, and therefore a climate change assessment requires a more detailed analysis of the particular infrastructure network. The KNMI scenarios have been used in a recent case study for the railway network in the Netherlands, and are tailor-made to obtain the right climatic information, spatially and temporally (Stipanovic-Oslakovic *et al.* 2012). UKCIP scenarios have been used in a number of studies (Glendinning *et al.* 2014; Sayers *et al.* 2015; Briggs *et al.* 2016).

Climate-driven processes that are of greatest concern

It is important to realize that climate change creates a dynamic environment where a steady state cannot be assumed (Dijkstra & Dixon 2010) when designing new infrastructure and when determining operating and maintenance strategies. It is also important to consider regional variations in the type and magnitude of climate change that is being or will be experienced.

In northern Europe, intensification of heavy precipitation and the elevation of the water table will reduce the infiltration capacity of the ground. As a consequence, erosion (surface and internal) and rainfall-induced slope instability are anticipated to increase. In addition, as snow, lake and river ice cover will decrease in northern Europe, frost action, related to freeze–thaw cycles, is another impact that is expected to damage engineered slopes. Finally, modification of vegetation regimes can be expected on existing engineered slopes in northern Europe owing to these features of climate change. All of the above processes and parameters need to be considered when assessing the stability of engineered slopes. A summary of the range of consequences of climate change is presented in Table 1 and Figure 4.

These impacts are slightly different for the other European regions. Whereas the climate change features are more moderate for NW Europe, the expected impacts will also be less important. For central and eastern Europe, increase of warm temperature extremes and decrease of summer precipitation are expected. As a consequence, the average soil water content and water level will decrease. Although the reduction of water content (and associated reduction of porewater pressure) may suggest that the risk of potential failure of engineered slopes will be reduced, other destabilizing factors such as desiccation cracking will come into play. The expected temperature rise in the Mediterranean region is larger than the European average and the annual precipitation is anticipated to be smaller. This suggests that a decrease of average soil water content and water table level can be expected. But again, any advantage gained by reduction in porewater pressures must be balanced against desiccation crack development and the development of preferential seepage paths permitting the rapid generation of high porewater pressures during incidents of extreme summer rainfall. As a result, the risk of rainfall-induced landslides remains; however, the events will be less frequent but potentially larger. Further details of these climate-driven processes are given below.

Water in the ground

Meteorological parameters such as precipitation, temperature and relative humidity form dominant components in a suite of factors

Table 1. *Potential climate change impacts on engineered slopes in Europe*

	Climate change features	Potential impacts	Potential failure modes	Processes and parameters to be considered
Northern Europe	Temperature rise much larger than global average	Snow, lake and river ice cover (−)	Damage risk from winter storms (+)	Drainage system
	Heavy precipitation (+) in winter and summer	River flows (+)	Rainfall-induced slope instability (++)	Shrink–swell of clay soil
		Evapotranspiration (++)	Surface and internal erosion (++)	Surface and internal erosion
		Infiltration capacity (−−)	Differential settlement (++)	Change of soil suction
		Average soil water content (++)	Crack development (++)	Vegetation
		Water table level (++)		Freeze–thaw cycles (only for northern Europe)
		Erosion (+)		
		Modification of vegetation (++)		
NW Europe	Annual mean temperature (+)	River flow (+)	Risk of river and coastal flooding (+)	
	Winter precipitation (+)	Evapotranspiration (+)	Rainfall-induced slope instability (+)	
		Infiltration capacity (−)	Surface and internal erosion (+)	
		Average soil water content (+)	Differential settlement (+)	
		Water table level (+)	Crack development (+)	
		Erosion (+)		
		Modification of vegetation (+)		
Central and eastern Europe	Warm temperature extremes (+)	Water temperature (+)	Rainfall-induced slope instability (+)	
	Summer precipitation (−)	Evapotranspiration (++)	Crack development (+)	
		Infiltration capacity (+)		
		Average soil water content (−)		
		Change in water table (−)		
		Erosion (−)		
Mediterranean Europe	Temperature rise larger than European average	Annual river flow (−)	Crack development (+)	
	Annual precipitation (−)	Evapotranspiration (++)		
		Infiltration capacity (+)		
		Average soil water content (−)		
		Water table level (−)		

++, Strong increase; +, moderate increase; −, moderate decrease; −−, strong decrease.

that influence the movement of water in and out of the near-surface slope materials. This includes soil infiltration, percolation, evaporation and temperature. In turn, these processes affect key soil parameters such as water content, soil water pressure and shear strength.

Water infiltration into soil is limited by the infiltration capacity and decreases with time during a rainfall event. Infiltration capacity depends on the type of soil, soil moisture content and soil cover, whereas permeability is mainly influenced by degree of saturation, porosity and soil water retention properties. Quantification of these parameters relevant to field conditions is critical if inputs into modelling are going to result in realistic outputs.

Laboratory methods can provide very controlled estimates of permeability, but are performed on relatively small, saturated, specimens and thus there are concerns about the representative nature of the results for the analysis of 'real' slopes. *In situ* characterizations are therefore, at least in theory, more relevant, but considerable variation in results is still observed. This can be attributed to macro-scale features that are not usually captured in the laboratory, but experience has shown that even good field experiments only partially capture spatial and temporal heterogeneities that can have a significant effect on mode inputs and modelled outcomes (e.g. Casini *et al.* 2013; Glendinning *et al.* 2014). The permeability of unsaturated soils is related to their soil water retention behaviour (Richards 1931; Fredlund *et al.* 1994; Romero *et al.* 1999) and more complex experimental methods are required to determine the hydraulic conductivity in unsaturated soils, compared with saturated soils (Askarinejad *et al.* 2014). Figure 5 shows the results for hydraulic conductivity calculated using the Horton infiltration model (Horton 1940). Several hydraulic parameters can be determined from the infiltration test; in addition to the soil infiltration capacity, permeability and rates of decrease in capacity can also be calculated.

- Key message: Types of monitoring systems and density of monitoring

Management of infrastructure networks requires a multi-scale approach (national, regional, line and slope scale). The types of monitoring systems and density of monitoring required to provide accurate and useful data at these different scales and within different European regions will vary. As an example, modelling and monitoring has shown the importance of local observations and measurements of meteorological factors. Although it is possible to derive relationships between meteorological parameters measured at distance from specific areas of interest, these relationships vary from site to site as they will be influenced by geomorphological factors. For researchers and asset owners to have accurate data for slope analysis and failure prediction, consideration should be given to the density and location of weather monitoring stations. Furthermore, practitioners should be aware that there are

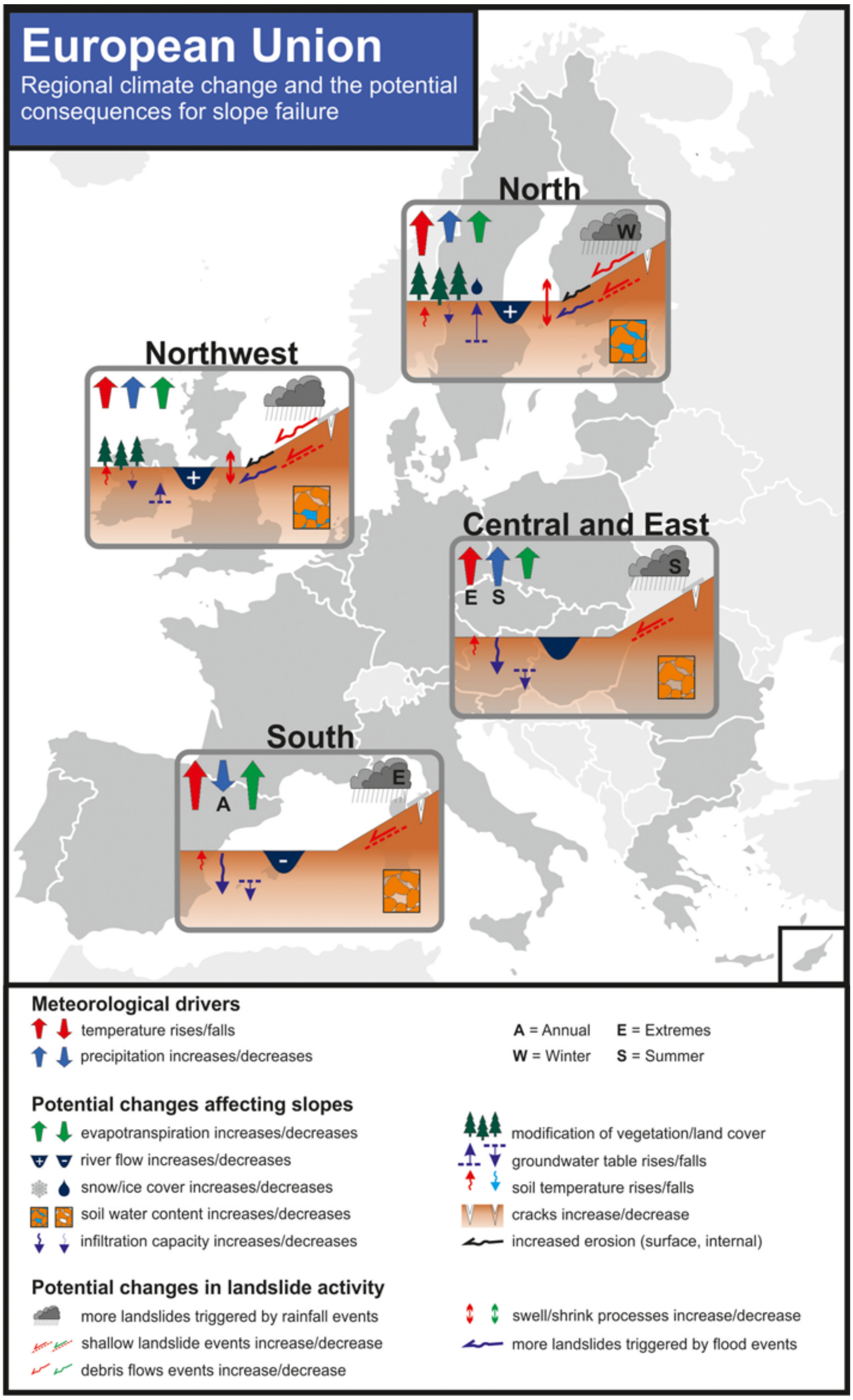

Fig. 4. European Union regional climate change and the potential consequences for slope failure.

risks when using only a weather monitoring approach to slope stability, as this may not capture the amount of water entering the ground.

Porewater pressure is the single most fundamental factor controlling the mechanics and hydraulics of soils. Treatment of most geotechnical problems involving volume change, deformation and strength requires that a portion of the stress applied to a soil is carried through a grain assemblage, and the other portion is carried by the fluid phases. This distinction is essential because an assemblage of grains in contact can resist both normal and shear stress, whereas water and air can carry normal stress but not shear stress.

In terms of hydraulics, water flow requires a driving potential (i.e. a hydraulic head difference, whereby the hydraulic head is the sum of the fluid pressure head and the elevation head), and soil water retention relates the soil water content to a capillary pressure. In the following sections, the fundamentals of water pressure at the particle level are explored by considering interface wettability effects, soil water retention and effects of suction on shear strength.

Slope hazards such as shrink–swell, erosion and landslides are studied as a three-phase system consisting of interfaces between minerals, liquids and air. In shallow, unsaturated soils, the water–mineral surface interaction is frequently assumed to be strong, with water menisci spreading on the soil particle surfaces and giving rise

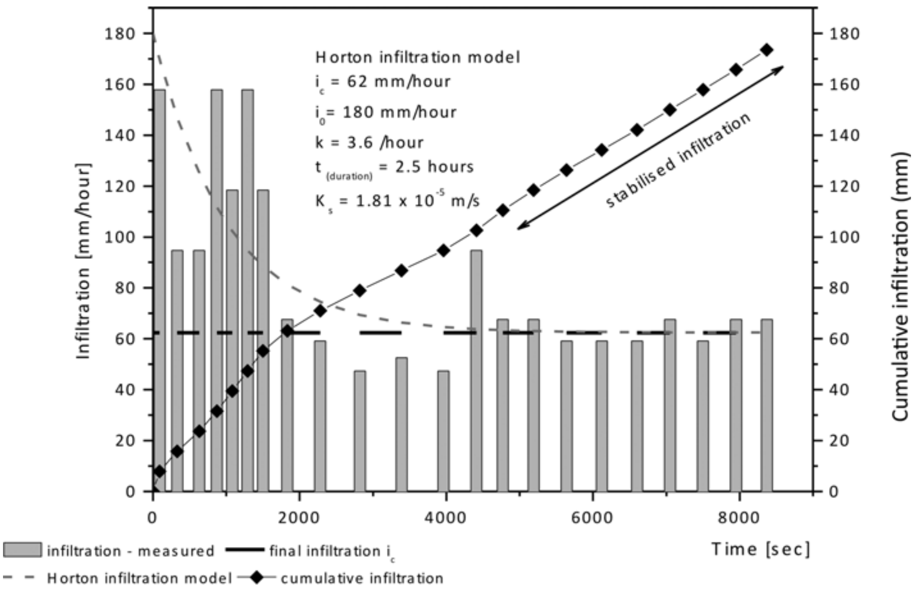

Fig. 5. Results from an infiltration test (using the double ring infiltrometer), conducted during the design phase of the Lešnica–Kronovo highway in Slovenia.

to concave menisci that provide suction and the increased shear strength that unsaturated soils are known for (Lourenço *et al.* 2012). However, there are more complex issues for biogeochemical interfaces, where water menisci interact with other interfaces that populate the pore space and the particle surfaces such as plant litter, bacteria, fungi and viruses (Totsche *et al.* 2010). Much research has been carried out in this field, but limited transfer into engineering geology and geotechnical engineering has been achieved to date.

Soil organic matter is a major constituent of soils (in particular at shallow depths) and is known to have a profound effect on the soil–water interaction. Soils rich in organic matter develop soil water repellency after long spells of hot weather and wildfires, which reduce or temporarily impede water infiltration, lead to preferential flow and enhance surface runoff (Doerr *et al.* 2006; Cannon *et al.* 2010). Soil particle wettability is also an unstable condition, where the soil switches to wettable or water-repellent at a critical water content. This instability is frequently explained by an interplay of microbiological activity (Jex *et al.* 1985), organic carbon dynamics (removal, transport and deposition) (Denef *et al.* 2001) and molecular rearrangements (Graber *et al.* 2009). Figure 6 shows an example of a water-repellent volcanic soil from Madeira Island (central Atlantic) with a contact angle for the water–solid interface of 122°. The water droplet was stable and rested on the surface for *c.* 2 h before infiltrating into the soil.

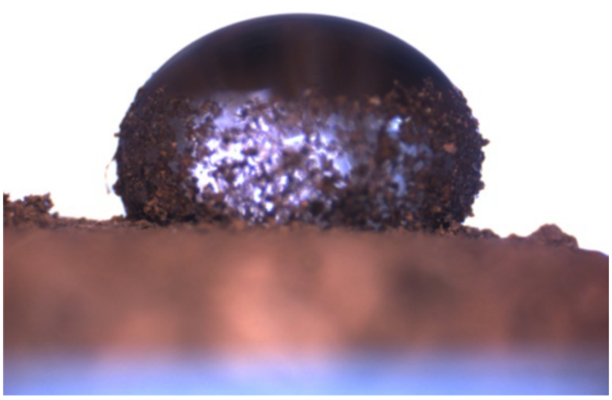

Fig. 6. Water droplet (diameter *c.* 6 mm) resting on a layer of air-dried water-repellent soils from Madeira Island (samples collected after a wildfire in September 2011).

- Key message: Soil wettability

The study of the mechanics of soils with variable wettability is still in its infancy in geotechnical engineering, with most of the research being carried out by soil scientists and hydrologists. However, with the increase in the frequency and intensity of extreme weather events, it is essential that wettability in soil–water interaction is addressed. Immediate challenges are related to its measurement (via contact angles) and its relation to porewater pressure and soil water content.

Soil water retention

Modelling water distribution and flow in unsaturated soils requires knowledge of the soil water retention curve (SWRC), which therefore plays a critical role in the prediction of fluid transport in the soil. The soil water retention properties are related to the pore size distribution, pore connectivity and pore shape, and angularity in the soil, which are governed by the soil type, density and structure (Or & Tuller 1999). Typically, a SWRC is highly nonlinear and hysteretic; that is, the corresponding retention functions of the wetting and drying paths are different (Mualem 1984). Generally, the soil has higher suction values at similar water content on the drying path compared with the wetting path.

A large variety of experimental techniques have been introduced to obtain the suction and water content values of soil sample to estimate the SWRCs, including pressure plate apparatus (Gardner 1956), the vapour equilibrium technique (Tang & Cui 2005), the axis translation technique (Hilf 1956) and *in situ* measurements (Pachepsky *et al.* 2001; Askarinejad *et al.* 2011). However, the experimental determination of the SWRC is a tedious and time-consuming process (Casini *et al.* 2013) and generally this covers only a limited number of points within the range of interest (Assouline *et al.* 1998) owing to the large range of suction in soils (several orders of magnitude), slow rate of equilibrium at high values of suction, and the difficulty in obtaining undisturbed samples (Tuller & Or 2004). Consequently, intensive efforts have been invested in developing mathematical functions to be fitted to the available set of measured points (Brooks & Corey 1964; Pachepsky *et al.* 1995). A commonly used parametric model was proposed by van Genuchten (1980).

Suction effects on shear strength

From the mechanical point of view, there are three stress components in an unsaturated soil: the total stress, σ, the pore water pressure, u_w, and pore air pressure, u_a. Fredlund & Morgenstern (1977) suggested that these can be combined into a pair of stress variables: net stress ($\sigma - u_a$) and matric suction ($u_a - u_w$). The matric suction defines the pressure difference across the air–water interfaces within the soil, and hence this controls the shape of the menisci. The menisci pull the soil particles together and increase the contact pressure between particles in the soil skeleton. In addition, the soil skeleton is also stabilized by surface tension forces, as noted by Burland (1965). The most commonly used approach to interpreting shear strength behaviour in unsaturated soils is to adopt an extended version of the traditional Mohr–Coulomb approach. This extension to unsaturated soils was put forward by Fredlund *et al.* (1978). Two separate friction angles can be used to represent the contribution to strength from the net stress and matric suction, giving the shear strength equation as

$$\tau = c' + (\sigma\_u_a) \tan \phi^a + (u_a\_u_w) \tan \phi^b \quad (1)$$

where τ is shear strength, c' is the effective cohesion, ϕ^a is the angle of friction for changes in net stress ($\sigma - u_a$), and ϕ^b is the angle of friction for changes in matrix suction ($u_a - u_w$).

This separates the effects of net stress ($\sigma - u_a$) and ($u_a - u_w$) and treats them differently.

Fredlund *et al.* (1978) suggested that the slope of the failure envelope in net stress space, ϕ^a, could be assumed to be equal to the effective stress angle of friction measured in saturated conditions (ϕ'). This would suggest that ϕ^a was constant for all values of matrix suction. However, Delage *et al.* (1987), Toll (2000) and Toll *et al.* (2008) have shown that ϕ^a cannot always be assumed to be equal to ϕ'. Toll (1990) and Toll & Ong (2003) have reported results of constant water content triaxial tests on unsaturated samples of tropical soils, a lateritic gravel from Kiunyu, Kenya and a residual sandy clay from Jurong, Singapore. The results are plotted in Figure 7, showing the variation of ϕ^a and ϕ^b with degree of saturation, S_r. The results show that at low degrees of saturation, ϕ^b becomes significantly lower than ϕ^a, and eventually drops to zero.

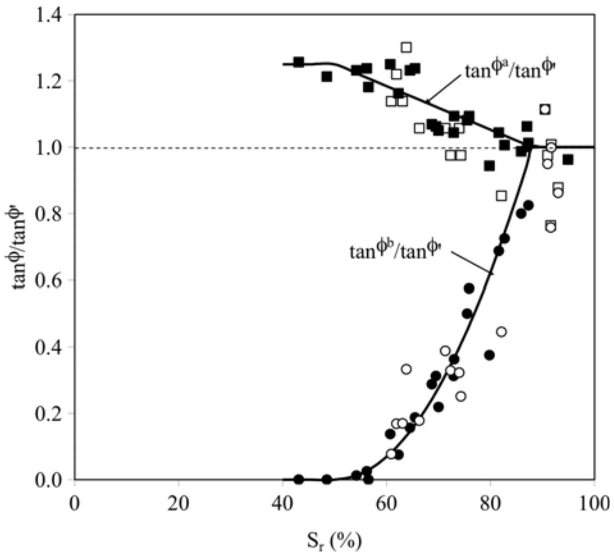

Fig. 7. Values for ϕ^a and ϕ^b related to degree of saturation for two tropical soils: filled symbols, Kiunyu Gravel (Toll 1990); open symbols, Jurong soil (Toll & Ong 2003).

Soil water movement: evaporation and deep percolation

Water percolates in the soil downwards (and laterally under unsaturated conditions). Flow may be inter-granular, being described by the Richards equation, or may follow preferential paths through macro-pores (i.e. clay desiccation cracks, rock fractures, fissures in sediments, worm holes or old root channels; Hendrickx & Walker 1997). Both flows may coexist. Either a stable descending wetting front is expected in the case of inter-granular flow, or fingered flow is generated, causing an unstable wetting front. Beven & Germann (2013) stated that soil water flow in macro-pores does not follow the conditions for which the Richards equation was derived, suggesting that in some instances, the representation of preferential flows as a Stokes flow provides a new impetus to addressing the problem. A review of models for inter-granular and macro-pore flows has been given by Šimůnek *et al.* (2003). Deep percolation corresponds to the amount of water that percolates to a specified soil depth. It may be calculated as a function of soil depth, using the same formulations as for flow in soil (e.g. Oliveira 2004).

Soil water evaporation

Evaporation is affected by various factors including wind speed, solar radiation, air relative humidity, soil texture (Noy-Meir 1973; Jalota & Prihar 1986), hydraulic conductivity (Wilson *et al.* 1994), water table position (Yang & Yanful 2002) and soil cracks (Tang *et al.* 2008, 2011; Cui *et al.* 2014). Initiation of the evaporation process needs to meet three requirements (Qiu & Ben-Asher 2010): (1) a continuous supply of evaporative energy; (2) a vapour pressure gradient between the evaporating surface and atmosphere, and the vapour being transported away by diffusion and/or convection; (3) a continual supply of water from the soil to the evaporating surface.

Song *et al.* (2013, 2014) developed a large-scale environmental chamber and carried out an evaporation test on Fontainebleau sand. The evaporation rate is calculated based on the water vapour balance between the inlet and the outlet of the chamber (Aluwihare & Watanabe 2003). Figure 8 shows a typical result of the actual evaporation rate along with the evolution of suction gradient between the soil surface and 77 mm depth. Three phases can be identified for the evaporation rate: the rate decreases slightly during the first 6 days, it decreases rapidly in the next 4 days, and finally the value decreases slowly. The suction gradient changes slowly from the initiation of evaporation, until it increases abruptly after 8 days. The high suction gradient corresponds to the significant decrease of evaporation rate, indicating the increase of soil resistance to evaporation by suction increase.

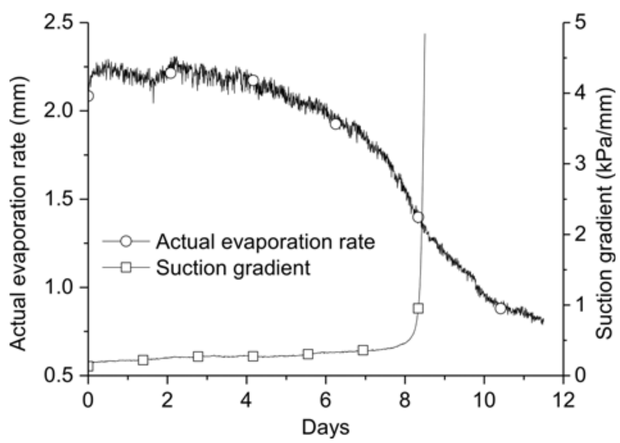

Fig. 8. Evolution of actual evaporation rate and suction gradient between soil surface and 77 mm depth during an evaporation experiment on Fontainebleau sand (Song *et al.* 2013).

Soil temperature

Temperature affects the rate at which processes can operate. At greater ambient air temperatures larger evaporative fluxes are expected to occur, resulting in more efficient drying out of soils and reduction of soil moisture contents, enhancing suctions and leading to greater soil moisture deficits. Another important factor to consider is the number of days in a year when air temperature fluctuation leads to freeze–thaw cycling in engineered transport infrastructure slopes.

Repeated freezing and thawing cycles in seasonal frozen regions affect the behaviour of engineered slopes in infrastructure and thus also affect the operation of infrastructure. Formation of ice lenses in the freezing zone is one of the primary reasons for frost action processes. This might result in soil strength and stiffness reduction or detrimental frost heave on the infrastructure surface, when the weight of structures is exceeded by heave pressure caused by the ice lens below (Baba 1993; Andersland & Ladanyi 1994).

In addition, suction of water into a frost-susceptible soil layer plays an essential role in the case of segregation freezing, which occurs in unsaturated frost-susceptible soils when available moisture and freezing temperatures coincide. Water drawn from outside, or from underlying unfrozen soil, allows the growth of ice lenses at the freezing front. Whereas the capillary theory (Chamberlain 1981; Loch 1981) is based on matric suction and assumes ice lens formation only in the freezing front, thermodynamic equilibrium surveys (Henry 2000) highlight also the under-pressure developed in the partly frozen zone, which sucks extra water from unfrozen soil into the ice lens formation zone (Konrad & Morgenstern 1980). As freezing of porewater starts in the middle of the pore space (Nieminen 1989), the remaining unfrozen adsorption water covering the surfaces of grains presents a water-conducting path in a partly frozen soil. It allows water to flow from the unfrozen layers below to the growing ice lens above (Nurmikolu 2005). Thus frost-susceptibility of soil depends primarily on its suction characteristics and hydraulic conductivity of the partly frozen soil (Bohar *et al.* 2012). Coarse-grained soils have high water permeability but small specific surface area, and, vice versa, fine-grained soils have high specific surface area but low permeability. Therefore silty soils often exhibit the highest frost-susceptibility. The assessment is normally based on grading but should be complemented by index tests such as consistency properties, pore size distribution, specific surface area, fines factor, water retention capacity, capillary rise, water permeability, etc. as suggested by ISSMFE (1989).

- Key message: Soil temperature measurement

Baker & Ruschy (1995) stated that it is essential to monitor temperature correctly, to assess the statistics of freeze–thaw cycles that influence the process of deterioration. A case study for the Netherlands shows that air temperature measured at a meteorological observation site (Schiphol) is different from the temperature observed at the road surface. However, it is possible to derive relations between the two temperatures with a consistent correlation. This is important, as this allows the assessment of freeze–thaw activity under changing climate conditions, as stated by Ho & Gough (2006).

Soil–vegetation interactions

Vegetation extracts water from deeper soil layers and evaporates it to the atmosphere. Processes in the soil and vegetation, including transport of water, solutes and energy, are strongly influenced by atmospheric processes (e.g. evaporation and precipitation; Moene & van Dam 2014). The vegetation on a slope often enhances slope stability of embankments and cuttings owing to mechanical (strengthening) and hydrological (drying out) factors. From a mechanical perspective, roots help the soil reinforcement through their tensile strength, adhesive and frictional properties. In terms of the hydrological effects of roots, they aid in reducing the soil moisture and effectively dissipating the pore water pressure through evapotranspiration and water absorption via the fine roots (Prandini *et al.* 1977; Coppin & Richards 1990; Greenwood *et al.* 2004; Schwarz *et al.* 2010; Springman *et al.* 2013; Yildiz *et al.* 2015).

Water uptake capacity, rooting depth and salt concentration in the ground form key components to determine evapotranspiration boundary conditions for the modelling of (un)saturated flow in soils (e.g. Hargreaves 1994; Pereira *et al.* 1999). Transpiration rates from different plants depend strongly on the development and architecture of the root system (Anderson *et al.* 1987; Berntson 1994; Lynch 1995). Water extraction by roots on a microscopic (single root) level was first developed by Philip (1957), but macroscopic models considering whole root systems have become more popular; for example, that of Gardner (1964) for a non-uniform root system. Since then, significant advances have been achieved; for example, Hemmati *et al.* (2009, 2012) developed fully coupled thermo-hydro-mechanical numerical analyses that consider transpiration from trees.

Traditionally, an increase in soil cohesion has usually been used to quantify the reinforcing effect of roots; for example, the Waldron and Wu model (WWM; Waldron 1977; Wu *et al.* 1979). The model takes vertical roots extending across a potential sliding plane in a slope into account and an increase in shear strength of soil is expressed as an additional cohesion (c_r), which is a function of the root area ratio (R_{AR}, the ratio of the cross-sectional area occupied by roots to the total area of the soil being considered) and the mean tensile strength of the roots, T_R (Gray & Sotir 1996). The WWM is based on the assumption that all roots break simultaneously. Other researchers have proposed that the additional shear strength is provided through enhanced interlocking and hence dilation (Frei *et al.* 2003). Pollen & Simon (2005) adapted a fibre bundle model (FBM) taking into account the successive breakage of root elements, according to their individual tensile resistance. The method is based on the assumption that the load applied to a breaking root is redistributed to neighbouring roots. The root tensile strength depends on species and site-specific factors: the values can reach more than 70 MPa and are usually greater than 2 MPa, but in most cases they range between 10 and 40 MPa (Schiechtl 1980; Stokes *et al.* 2008).

Mattia *et al.* (2005) have investigated the relationship between root diameter and root tensile strength (Fig. 9) by studying *Lygeum spartum* L. (a perennial monocotyledonous herbaceous species), *Atriplex halimus* L. and *Pistacia lentiscus* L. (two dicotyledonous shrub species) collected in the Basilicata region (southern Italy) by *in situ* excavation. Estimation of root reinforcement of native species is a major issue in research, as quantification is required in soil bioengineering techniques.

- Key message: Vegetation management

Management of existing vegetation and replacement of vegetation with new species can result in improvements of slope stability and reduce erosion (internal and along the surface). It can also result in managing soil moisture fluctuations in the near-surface zone to reduce potential for cracks to form and to prevent significant shrinkage during drought.

Although there is general agreement that the presence of plant roots increases soil strength both through mechanical enhancement and reduction in pore water pressure, the magnitude and reliability of these strength gains are difficult to quantify (Switala *et al.* 2017). This knowledge gap limits the utilization of managed vegetation in

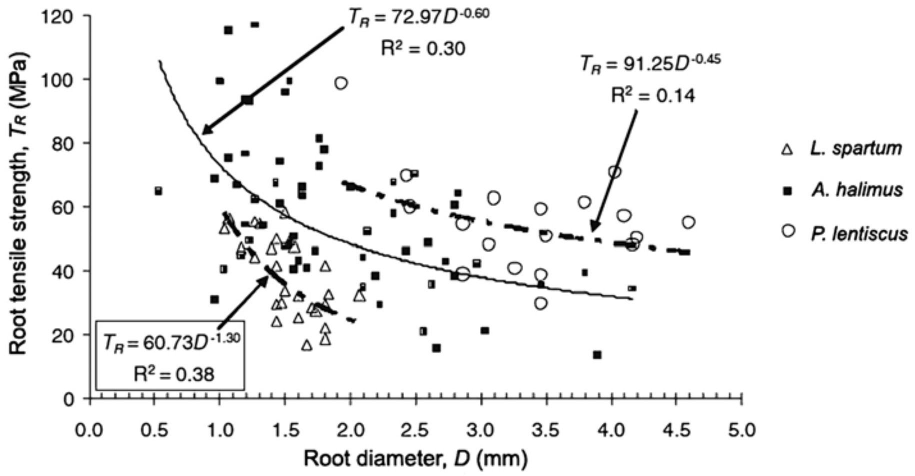

Fig. 9. Relationship between root tensile strength (T_R) and root diameter (D) (modified from Mattia *et al.* 2005).

slope design and slope asset management. Managed vegetation has the potential to provide an economic, soft engineering, solution for engineered slope stabilization but while there is uncertainty over its effectiveness utilization of this technique will be limited.

Cracking

Cracking on the surface of slopes increases the transmission of rainwater and is recognized as a mechanism for accelerated porewater pressure response in slopes (Anderson *et al.* 1982; Zhan *et al.* 2006; Rouainia *et al.* 2009). Conversely, cracking indicates the development of a desiccated layer possessing extremely low unsaturated permeability that inhibits the transmission of soil water to the evaporative surface.

Cracks initiate when the tensile strength of the soil is exceeded by drying-induced tensile stresses. Theoretical expressions for the tensile strength, as a function of saturation state, have long been established (Schubert 1975; Snyder & Miller 1985; Lu & Likos 2004) and many generalized relationships have been proposed (Venkataramana *et al.* 2009). A range of test methods have been employed to measure the tensile behaviour of soils prone to cracking, as described by Vanicek (2013); these include triaxial, bending, hollow cylinder, unconfined penetration, indirect and direct methods.

An adaptation to a direct shear apparatus was used by Stirling *et al.* (2013). The results show that the re-drying path exhibited a pronounced loss in strength relative to the initial drying path, suggested to be due to a combination of soil water hysteresis, chemico-mineralogical changes and an irreversible change in the soil structure following desiccation. This would lead to an increased occurrence of the cracking criterion until equilibrium is eventually reached, as also demonstrated by Tang *et al.* (2011).

Experiments have been conducted aiming at understanding the initiation and propagation mechanisms of desiccation cracks (Miller *et al.* 1998; Rodríguez *et al.* 2007; Péron *et al.* 2009*b*; Tang *et al.* 2011; Lakshmikantha *et al.* 2012). Cui *et al.* (2013, 2014) described a large-scale environmental chamber that was developed for carrying out physical model desiccation tests. It was found that in the compacted Romainville clay soil used, cracks initiated at high volumetric water contents (60%). The evolution of surface crack ratio and average crack width were found to be very consistent, indicating that prediction of crack development is possible.

The inclusion of cracking in modelling of the near-surface zone of a slope represents a step forward in the accuracy of the moisture exchange boundary condition. Desiccation crack modelling approaches are varied and stem from the earliest linear elastic fracture mechanics concepts (Lachenbruch 1961; Morris *et al.* 1992; Ayad *et al.* 1997) to proposed stable tensile stress failure (Kodikara & Choi 2006; Péron *et al.* 2009*a*).

Recently, unsaturated soil behaviour has been included in the modelling of compacted fill, typical of engineered infrastructure embankments (Stirling *et al.* 2013; Stirling 2014). The formation of cracks subject to a tensile failure criterion has been included in a continuum finite-difference mesh, FLAC 2D two-phase flow. This has allowed the distribution of fluid throughout the modelled clay to be captured by application of an evaporative boundary condition. Primary, fully penetrating cracking is shown to correspond to the approaching air-entry value at the drying surface. Continued drying results in steady opening of existing cracks until, upon prolonged drying, an increasingly shallow region of elevated suction causes the disintegration of a desiccated crust. Inclusion of such processes is believed to influence the hydrological behaviour of the desiccated slope surface strongly.

- Key message: The impact of desiccation cracking on the rates of infiltration and strength of slope material

Understanding the effects of micro- and macro-scale cracking on engineered slope hydraulic and mechanical behaviour is essential if the impacts of a changing climate on engineered slope stability are to be fully evaluated. Crack development in engineered soils has been studied in the laboratory but prediction of crack development in field conditions, where a greater number of variables (spatial variations in wetting and drying, root reinforcement, surface drainage pathways) come in to play, remains a significant challenge. Monitoring and assessing crack formation at field scale presents a significant technical challenge. There is a pressing need to develop remote sensing tools, such as LiDAR and geophysical techniques, to quantify cracking, and to incorporate these data into predictive numerical models.

Accelerated ageing effects

- Key message: Changes in microstructure or mineralogy caused by exposure to ‘new’ climatic conditions (accelerated ageing effects)

Repeated cycles of wetting and drying of fine-grained soils have been shown to change the microstructure of engineered fills (Stirling *et al.* 2014), and thus alter the mechanical and hydraulic properties of the soils. The limits to the extent of this alteration have not yet been fully explored, and it is not currently known how much reduction in strength or change in permeability may be caused by these mechanisms (Elia *et al.* 2017; Smethurst *et al.* 2017). Long-term changes in soil engineering properties have significant implications for slope stability and asset management.

Erosion

Erosion is one of the most common causes of earth structures damage and failure. It is estimated that, annually throughout the world, overall soil loss owing to erosion is 200 m^3 ha^{-1} (Koda *et al.* 2013). The process of erosion is not only an environmental issue, as it leads to pollution, increased flooding and sedimentation, but is also recognized to be a serious concern for civil engineers, as it can severely affect the stability of engineered slopes.

Engineered slopes are extremely sensitive to accelerated water erosion, especially during construction and initial exploitation phases. Surface runoff from the crest of slopes is observed on most types of earth structures such as road embankments, levees, dams or landfills. Soil erosion is a dual process caused by detachment of aggregates from soil mass, deriving from erosive agents such as water and wind (Cuomo & Della Sala 2013). A wide range of examples demonstrates the effects of surface erosion on engineered slopes (Gajewska 2010; De Oña *et al.* 2011; Koda & Osiński 2016) and it is concluded that most of them could have been prevented by properly selected erosion control measures. One of the main challenges arising during design of the slope reinforcement is to include the vegetation cover or geotextile reinforcement when analysing the stability. Properly selected plants, with nutrition-rich bedding, could be introduced on slopes and significantly improve the erosion control systems.

Internal erosion is recognized as one of the most severe and most common causes of failures of earth structures. The phenomenon, which is also known as 'piping', affects especially structures that are located under conditions of high water levels, exposed to extreme or persistent water flows or that are at risk of seismic movements. The numerous case studies analysed throughout the last century have helped us to recognize the main paths and the locations of internal erosion, as it progresses in earth structures. Four main categories of piping processes can be distinguished: (1) internal erosion through slopes or embankments; (2) internal erosion through the foundation; (3) internal erosion of the embankment into the foundation; (4) internal erosion along, or into, embedded structures.

In particular, the process of backward erosion, by which shallow pipes form in a granular layer under a fine-grained cover layer, is an important failure mechanism for dams and levees. Backward erosion piping has been studied experimentally by various researchers (Van Beek *et al.* 2011, 2014).

- Key message: Erosion mechanisms (surface, internal, backward) present an increasingly important risk for engineered slopes and earth structures, which can be combated by implementation of erosion control measures

Key aspects that need to be considered by designers and operators

Design of monitoring systems for new slopes and existing sections of infrastructure

Technical advances in instrumentation have improved the accuracy and increased the range of information that can be obtained via monitoring. Furthermore, advances in communication systems have reduced the operator time required to collect monitored data and provide a pathway for more efficient analysis by combining multiple datasets (Smethurst *et al.* 2017). The interactions of soil, atmosphere and vegetation make engineered slopes complex systems, and monitoring a limited number of parameters (e.g. displacement, rainfall and porewater pressure) may not be sufficient to identify failure mechanisms. Combining geotechnical and environmental monitoring systems with vegetation data and surface condition data from remote surveys presents a possible solution.

The location of environmental monitoring for slope risk (weather stations) requires careful consideration (Ho & Gough 2006; Hughes *et al.* 2009; Askarinejad & Springman 2017; Smethurst *et al.* 2017), as local factors may mean that readings are not adequately representative of the full area that a single monitoring station is taken to represent. Increased density of monitoring points and combination of monitoring data with radar and satellite information has the potential to improve accuracy.

The construction of new engineered slopes presents an opportunity to design intelligent monitoring systems. Installing systems during construction rather than retrofitting has significant cost advantages.

Vegetation management and slope stability

Several studies have investigated the effect of vegetation on the stability of slopes and the results can be summarized as: (1) increase in the shear strength of the soil at the shear band (basal and lateral) owing to the added tensile strength of the roots (Askarinejad *et al.* 2012); (2) overturning effect of wind on the trees (Hsi & Nath 1970; Brown & Sheu 1975); (3) additional weight of the vegetation on the slope (Coppin & Richards 1990; Greenwood *et al.* 2004); (4) changes in the soil water content and hence porewater pressure owing to the root water uptake and evapotranspiration (Osman & Barakbah 2006; Springman *et al.* 2013; Askarinejad & Springman 2014); (5) extension and deepening of desiccation cracks in dry periods, which might ease the flow of water towards the slip surface (Greenwood *et al.* 2004).

A series of centrifuge model tests was performed to investigate the hydro-mechanical responses of a silty sand slope subjected to rainfall. A climate chamber and rain simulator were designed and constructed for a 2.2 m diameter drum centrifuge (Springman *et al.* 2001). The effects of roots on the behaviour of unsaturated slopes subjected to rainfall were investigated by comparing the development of porewater pressure and displacement for a vegetated and an equivalent non-vegetated slope. The contribution of the roots to the shear strength of the soil was quantified using a series of direct shear tests. The observations from the centrifuge tests indicate that the vegetated slopes were very well drained during the application of rainfall, compared with the non-vegetated slopes, and no overland flow or ponding of water at the toe of the slopes was seen. This could be due to the increase of the macro-permeability of the slope because of the penetration of the roots, which helped the rainwater to percolate into the soil. The rate of slope deformation generally reduced as the root reinforcement mechanism was activated. The centrifuge tests revealed that the vegetated slope acted in a more ductile fashion compared with the slope without additional root reinforcement. This observation indicates that larger deformations might be expected prior to failure in the slopes with a well-developed network of roots, compared with the non-vegetated slopes. However, the interconnected network of roots might cause a larger volume of unstable soil mass to be mobilized during failure.

Conclusions

This paper provides a selective overview of the atmosphere–vegetation–soil interactions, and their impacts on engineered slopes. Even from this partial overview, it is clear that climate-driven processes are of great concern. As climate change does not affect the whole European region equally, the consequences will vary from region to region (see information presented in Table 1 and Fig. 4). We highlight here some of the issues that we feel require specific attention in further research and development.

(1) Surface and internal erosion (primarily a concern in northern and NW Europe). Increases in precipitation and wind will increase the magnitude of erosion from the surface of slopes. This will be exacerbated by any reductions in vegetative cover caused by preceding drought periods. Implications of increased erosion are exposure of engineered fill to increased infiltration during storm events, making slopes more vulnerable to deep-seated failures and also increased incidences of debris being washed onto highways and railway lines. Selection of appropriate erosion protection measures will be required to safeguard new and existing slopes.
(2) Surface cracking (a concern in all zones). Increased frequency, duration and intensity of drought periods will lead to an increase in surface desiccation cracking. These cracks provide infiltration pathways and have the potential to increase the transmission of rainwater into slopes, leading to accelerated porewater pressure responses and increases in surface and internal erosion, and thus may also lead to increased volume of debris or a failure event. Crack propagation with repeated cycles of drying and rewetting also has the potential to reduce slope stability by creating planes of weakness that may develop into shear zones.
(3) Freeze–thaw action (primarily a concern in northern Europe). Climate predictions indicate that average annual land temperatures in Europe will increase, particularly in northern and eastern Europe during winter. This suggests that instances of frost heave will be less frequent. However, increased climatic variability has the potential to cycle soils between a frozen and unfrozen state more frequently, with consequent cumulative damage to soil structure and reduction in strength and stiffness. Loss of permafrost in the far north and in the Alps may have consequences for large slope instability, even on very gentle gradients (a few degrees).
(4) Wetting or saturation and rainfall-induced failure (primarily a concern in northern and NW Europe). Increased average rainfall, higher numbers of extreme events and higher intensity storm events will increase porewater pressures and hence decrease the overall stability of slopes. These effects are likely to be exacerbated by surface damage caused by erosion and surface cracking mentioned in previous sections, facilitating rapid porewater-pressure response and potentially more rapid transition of engineered slopes from a stable to an unstable state. Designers should consider appropriate use of drainage systems and of managed vegetation to protect against surface erosion and to increase evapotranspiration.
(5) Shrink–swell behaviour (a concern in all zones). Increased annual temperatures will lead to significant volume reductions in plastic soils during summer months and hence greater amplitudes of volume change. More variable precipitation, particularly increases in summer storm events, will also induce an increased frequency of shrink–swell cycles. This has implications for the alignment of railway tracks and highways, and has the potential to accelerate progressive failure mechanisms within engineered slopes.

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